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NAVIGATOR PERFORMANCE STUDIES FOR SPACE NAVIGATION USING THE NASA CV-990 RESEARCH AIRCRAFT

by Richard A. Acken and Donald W. Smith

Ames Research Center
Moffett Field, Calif.

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SUMMARY

Manually operated hand-held sextants are being studied at Ames Research Center to determine whether they are sufficiently accurate for midcourse navigation phases of manned space flight. Studies carried out on the ground have been extended by using the NASA CV-990 aircraft to provide sighting conditions closely simulating those in spacecraft and to investigate further the measurement error due to lunar irradiance. The results of approximately 1200 measurements made during nine flights confirm results of simulator and ground-based studies which indicate that, with a hand-held sextant, an astronaut can be expected to make navigational measurements with errors having a standard deviation of approximately ±10 arc seconds. A value for moon irradiance effect of approximately 25 arc seconds was established for the conditions of the experiment using a hand-held sextant.

INTRODUCTION

The manually operated hand-held sextant has provided marine navigators with a compact, lightweight, easily operated instrument for centuries. Sextants developed for aircraft navigators are more accurate and provide higher operational reliability. Now, in the space age, with accuracy, reliability, weight, and size at a greater premium than ever before, attention has again been focused on the manually operated hand-held sextant for navigation in space operations, during the orbital, rendezvous, and midcourse phases of flight.

New sextants have been developed to meet the increased accuracy and reliability requirements in the spacecraft environment. The performance of the operator-instrument combination has been studied at Ames Research Center in a variety of ground-based simulators with simulated celestial targets and a ground observatory from which the angles between actual stars and the moon were measured. The simulator studies have indicated that a navigator using a hand-held sextant is capable of making navigation measurements with measurement errors having a standard deviation of approximately ±10 arc seconds with a small measurement bias. The studies conducted at the ground observatory indicate a similar standard deviation of measurement error. However, the measurement bias errors for the observatory data were more variable. It was thought that this variability was due to an inability to correctly compute the atmospheric refraction corrections since they are based on standard pressure-temperature lapse rates through the atmosphere, and any disturbance such as a temperature inversion, or localized heating caused by neighboring buildings or ground areas would cause the corrections to be in error. In order to adequately evaluate the instrument-operator performance, therefore, it became necessary to find some means by which the computational problems associated with atmospheric refraction corrections could be circumvented. The CV-990 aircraft provides the means since sextant measurements can be made at high altitude where atmospheric anomalies are minimized.

Furthermore, it is necessary to confirm that results similar to those obtained in ground-based simulators and from a ground observatory can be obtained from a spacecraft in flight. Through experience gained in the Gemini program, it has become evident that only a very limited amount of sighting performance data, which is statistical, can be obtained from a single space flight. The NASA CV-990 aircraft provides an excellent opportunity for obtaining a large quantity of such data in a realistic, near-space, operational environment for better evaluating navigator-instrument effectiveness.

The objectives of the aircraft studies therefore were twofold: first, to extend results of simulator and ground-observatory sextant sighting studies into a near-space environment; and second, to alleviate the problems associated with computing atmospheric refraction corrections when real celestial targets are used, by flying at high altitudes above those portions of the atmosphere where large anomalies can be expected. It was expected that the latter would make it possible to investigate further the magnitude of measurement errors due to irradiance effects such as those found in making star-lunar-limb, or lunar-limb-lunar-limb measurements since it was anticipated that the variability in the measurement bias errors would be reduced.

The advantages of the flying laboratory therefore are: (a) the instrument operator in the aircraft environment must cope with many problems similar to those confronted by a spacecraft navigator, such as, a limited field of view for target identification, sighting through a pressurized window, and sighting from a vehicle moving in yaw, pitch, and roll; (b) making sextant measurements from high altitudes greatly reduces the error in computation of atmospheric refraction which could result from atmospheric anomalies such as temperature inversions and localized heating; (c) measuring the angles between actual celestial targets from the ground observatory is highly dependent on the weather; since the aircraft flies at high altitude above the weather, experiments can be scheduled to take advantage of the best target conditions.

It should be noted that in order to compute the atmospheric refraction correction with the desired accuracy, the aircraft position and altitude had to be known within less than 1 nautical mile. In order to obtain the aircraft position and altitude with this accuracy, it was necessary to use radar tracking during the sighting periods. The experimental flights were therefore made over the High Range at the Flight Research Center where the required radar tracking was provided.

Four subjects participated in this study. They were engineers working in related studies at Ames Research Center. One of the subjects, the author (Richard A. Acken), was also a currently rated Air Force navigator.

NOTATION

n	number of observations in a data run
CA	corrected computed angle, arc sec
OA	corrected observed angle, arc sec
ϵ	measurement error for one sighting OA-CA, arc sec
$\bar{\epsilon}$	(algebraic mean) measurement error for one data run, arc sec
ϵ_{mean}	average (algebraic mean) error of all runs for one subject and one type of target, arc sec
σ	standard deviation, $\sqrt{\dfrac{\Sigma(\epsilon - \bar{\epsilon})^2}{n-1}}$, arc sec
σ_{mean}	average (algebraic mean) standard deviation of all runs for one subject and one type of target, arc sec

TEST EQUIPMENT

CV-990 Research Aircraft

The CV-990 (see fig. 1) is a Convair four-engine jet passenger transport with a range of about 3,300 nautical miles, a practical operating ceiling of about 41,000 feet, and a useful payload of about 20,000 pounds. Special view ports, power supplies, and other general use facilities and instrumentation

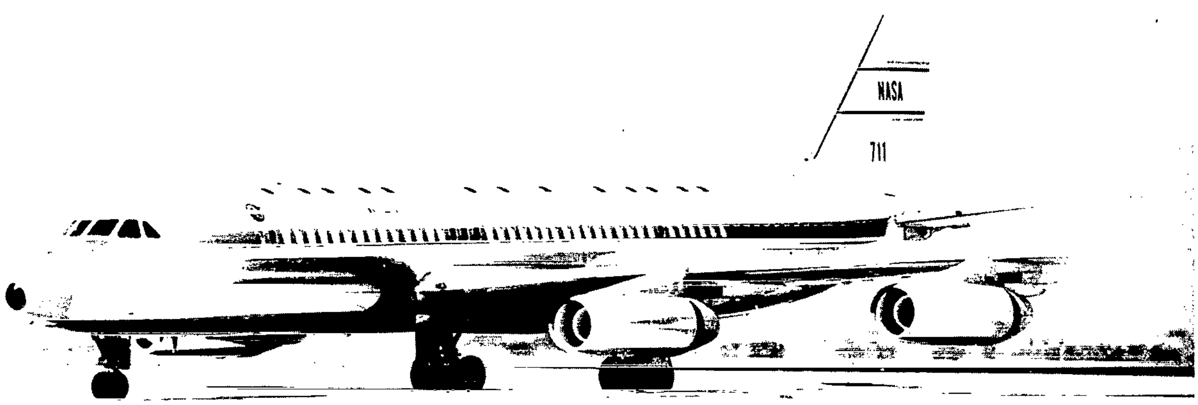

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Figure 1.- The NASA CV-990 research aircraft.

were installed. Converters provide 14 kVA of 60 Hz power to junction boxes spaced along the cabin. Normal 400 Hz aircraft power for experimenter use is also available (ref. 1 presents more details).

Observation Ports

Thirteen 12 × 14-inch cutouts were made into the left side of the fuselage at an elevation of 65°, and fitted with optical quality windows, 1 inch thick. The observation windows are ground and polished soda-lime plate glass, specially selected for minimum bubbles and striae. Each surface is flat to a maximum of 4 fringes of sodium light per inch and its surfaces are parallel to within a maximum of 0.001 inch across the entire pane. All panes have magnesium fluoride antireflection coatings on both sides.

The optical glass was held in aluminum frames with silicone-rubber gaskets. Each window assembly is installed from the cabin side of the port and presses against a gasket on the restraining edge of the fuselage skin. Two aluminum shoulders, 3 inches long, are then cinched against the inside of the frame. At high altitude the restraining shoulders are tightened and a positive, leakproof seal is produced by the pressure differential across the window.

Plastic safety windows are mounted on the inside of the observation windows. Sliding in horizontal tracks, they are moved out of the line of sight during the observation period. In the closed position, the safety windows press tightly against a gasket seal. (In case of failure of an optical window, the cabin pressure can be maintained.) The safety windows were opened by the observer only during the sighting periods.

Because of the very low outside temperatures (about -50° C) at operating altitudes, cabin moisture tends to condense on the inside of single pane windows. A defrosting system keeps the optical glass free of condensation. Warm air (about 40° C) is bled from the cabin air conditioner to openings across the top of each port and a manual butterfly valve controls the air flow across each window. Also, the exterior surface of the fuselage and each window is carefully cleaned and dried just before each flight.

Sighting Stations

Two sighting stations, 10 feet apart, were installed approximately midway in the passenger compartment. The forward station (fig. 2) was designed to hold a gimbal-mounted sextant. The station consisted of a platform to elevate

Figure 2.- Sighting station for gimbal mounted sextant.

Figure 3.- Sighting station for hand-held sextant.

the sextant and observer to the window, a seat adjustable vertically and horizontally, and a sextant mount adjustable in yaw, pitch, and roll. The aft sighting station (fig. 3) was designed for hand-held sextant use. It consisted simply of a platform and seat to raise the observer to the level of the window.

Both seats were easily adjustable, and specifically designed for flight stresses. Each seat was fitted with a safety belt which the observers wore at all times. The platforms were fastened to two passenger seat rails with special clamps. These seats were not used for take-off and landing, but only during the high altitude sighting periods.

Timing Station

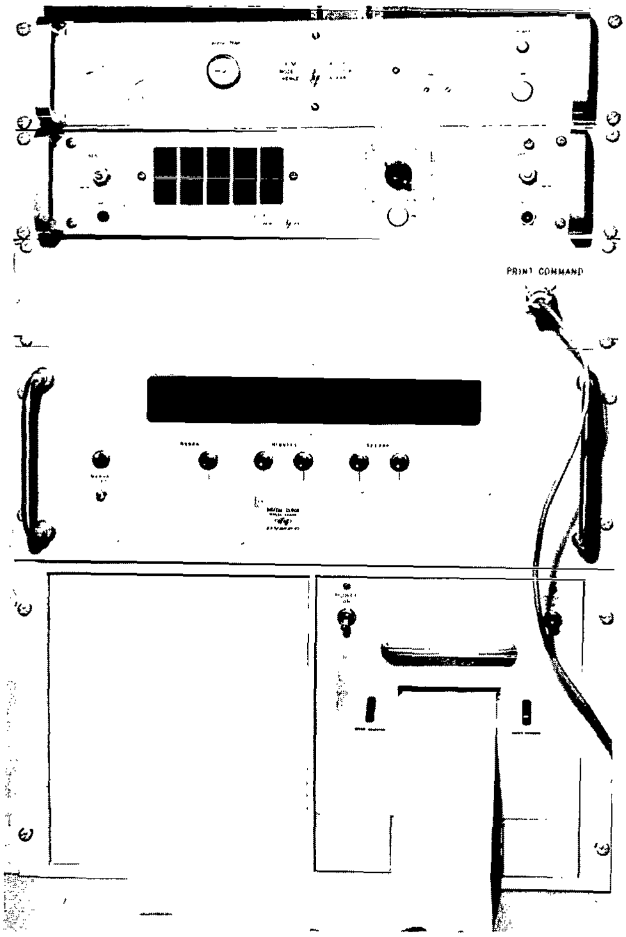


Figure 4.- Timing station.

A timing station (fig. 4) was located between the sighting stations. It consisted of an electronic counter, a digital clock, and a printer to record the time of observation on tape. The time in hours, minutes and seconds was clearly visible in the windows of the digital clock. The printer was triggered by a button on the gimbaled sextant near the adjustment knob. The time of observation with the hand-held sextant was recorded by the data keeper on a verbal command at target superposition. The clock was synchronized with the National Bureau of Standards radio time signal (station WWV) after take-off on each flight. The accuracy was ±1/2 second.

Sextants

Two different types of sextants were used in this investigation. The hand-held sextant was a modified space-rated D-9 sextant, developed by the Air Force and similar to the ones used on the Gemini flights GT-4 and GT-7. This sextant weighed approximately 6 pounds. The readout least count was 0.001° or 3.6 arc sec. The D-9 sextant has a 4.5 power telescope with a 15° field of view. The primary line of sight of the two-line-of-sight instrument can be filtered by either of two different neutral density filters. Only the more dense filter with a neutral density (N.D.) of 2.0 was used during this study. There is a lighted reticle within the telescope for centering the targets in the field of view. Further details concerning this sextant can be found in reference 2.

The gimbaled sextant was much larger and heavier than the hand-held sextant. When placed on the specially designed mount, this sextant could rotate about its three major axes (yaw, pitch, and roll). It should be emphasized that the gimbaled sextant is not a flight-rated instrument, nor was it intended to be. It was used during this investigation because its highly accurate readout (to 1 arc sec least count) and flat calibration curve (±1 arc sec) would provide baseline data for evaluating navigator performance and more accurate data for investigating the effect of irradiance on measurement accuracy. This sextant has a 10 power telescope, more than twice the magnification of the D-9, with a 5° field of view. The primary line of sight of this instrument can be filtered with any combination of three different density filters. Only the most dense filter, with a neutral density (N.D.) of 1.3, was used.

Radar Tracking Range

The flights were made over the High Range at the Flight Research Center because the accuracy required for the aircraft geographical position and altitude made it necessary to use radar tracking. The High Range is a radar tracking range in Nevada and California and is operated by NASA to track the X-15 and other research aircraft. The High Range radar is accurate to ±1500 feet in distance and ±400 feet in altitude at the maximum expected distance from the stations. In order to maintain the accuracy of the moon parallax correction to within ±1 arc sec, the geographical position of the aircraft had to be known to within 1 nautical mile. A transponder was installed on the aircraft to facilitate identification and increase the tracking accuracy.

TEST PROCEDURES

Task Description

The task in this study was to select a primary target through the sextant primary (fixed) line of sight and then to superimpose upon this target, a known star seen through the secondary (scanning) line of sight. The exact time and angle of target superposition were then recorded. When the moon was in the primary line of sight, the star in the secondary line of sight was superimposed on either the nearest or farthest limb (edge) on the moon. Filters were used for the primary line of sight to decrease the moon's brightness.

Although the observed angle between two stars would not be used in space for navigation purposes, this type of target was used in this study because it was felt that two stars would provide optimum targets for measuring human performance.

The four participants worked in teams of two; while one was sighting the other recorded data. After each participant had made a data run, consisting of 10 consecutive sightings, the teams changed from one sighting station to the other and continued the same procedure using a different sextant.

Performance Criteria

Sighting performance was evaluated by two different criteria: (1) the measurement bias error, and (2) the standard deviations of measurement error.

In the evaluation of the performance of the operator-instrument combination, it is necessary to determine the magnitude of both the consistent (bias) errors and the random errors in the measurement process. The measurement error, ϵ, is defined as the difference between the corrected observed angle, OA, and the corrected computed angle, CA.

$$\epsilon = OA - CA$$

The measurement error averaged over a data run, $\bar{\epsilon}$, is calculated by taking the algebraic average of the measurement errors for a given data run. The standard deviation, σ, for a data run is

$$\sigma = \sqrt{\frac{\Sigma(\epsilon - \bar{\epsilon})^2}{n-1}}$$

The computed angle, which was the criterion for determining the magnitude of the measurement errors, was calculated through the use of a digital computer program developed at Ames for this purpose. The digital program computes the angle between two stars or between a star and a lunar limb or lunar landmark, accounting for longitudinal, latitudinal, physical and diurnal librations, aberration, atmospheric refraction, and parallax as seen from the aircraft at variable topographical positions and altitudes.

The observed angles were corrected for (1) difference in index of refraction of the environment inside and outside the aircraft, (2) window deviation, (3) sextant calibration, and (4) filter bias error when a filter was used.

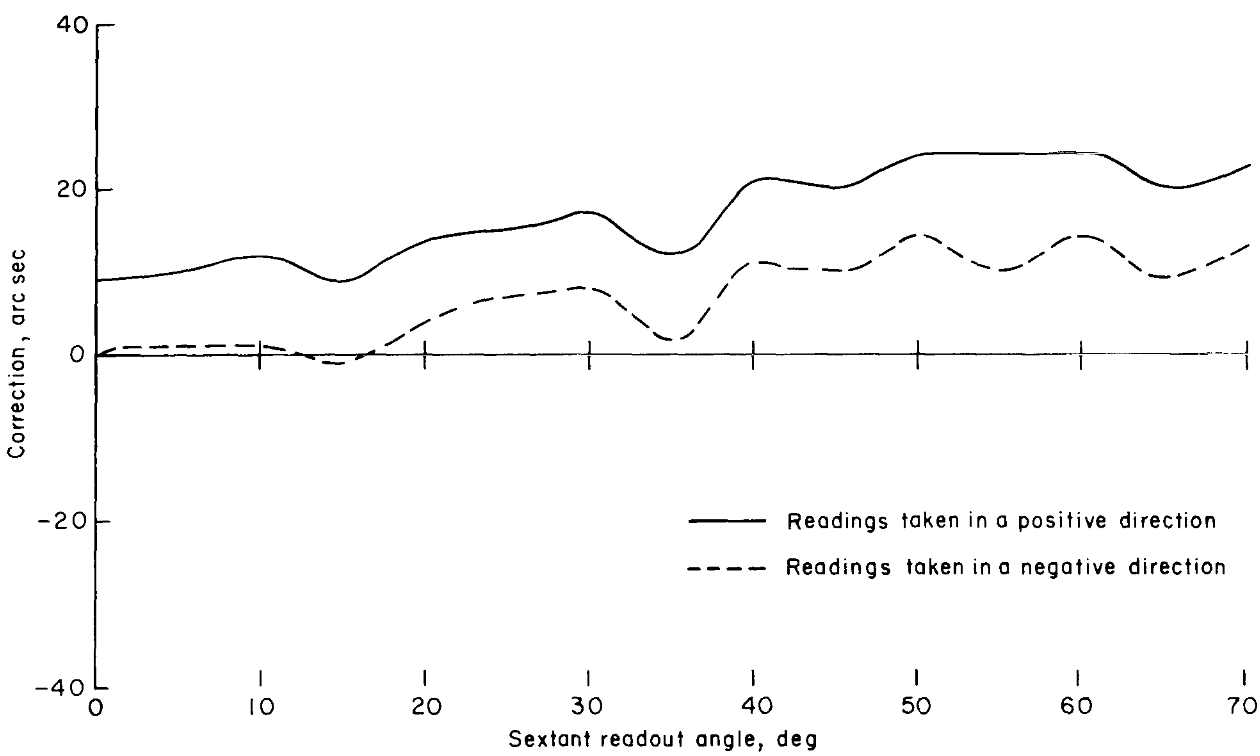


Figure 5.- Hand-held sextant calibration curve.

The sextant mechanical deviations and the filter bias errors were corrected by means of calibration curves for the respective instrument. These calibrations were made with precise laboratory equipment. The accuracy of the testing arrangement was judged to be about ±3 arc sec. The calibration curve for the hand-held sextant is shown in figure 5.

Comstock's equation was used to compute the effect of atmospheric refraction

$$r = \frac{983b}{460 + T} \tan Z$$

where

r refraction angle in arc seconds

b barometric pressure in inches Hg

T temperature in degrees F

Z zenith angle

This formula, which can be found in reference 3, is accurate to ±1 arc sec for a Z as large as 75°. For this study, the atmospheric refraction was quite small because of the high altitude of the aircraft and small zenith angles of the targets chosen.

The corrections for errors due to index of refraction difference and window deviations, which are caused by bowing due to pressure differences and window surface flatness and wedge, were computed with a digital computer program developed at Ames for this purpose. Actual flatness and wedge measurements were made on the windows used in flight. These results plus the actual pressure difference across the window, recorded in flight during the sighting periods, were fed into the computer program which calculated the window deflection due to pressure and the line-of-sight deviations for the given or actual angles of incidence and window positions. Because of the thickness of the windows, the maximum deflection was less than 4×10^{-5} inch. This correction was the most difficult to compute because the window positions of the two sextant lines of sight had to be estimated and the normal rolling action of the aircraft in flight constantly changed the angles of incidence. However, because of the quality of the windows and their small deflection, the corrections were small (ranging from +6 to -8 arc sec) and it is felt that the accuracy is within ±4 seconds.

Test Subjects

The four subjects participating in this investigation were Ames Research Center engineers. Subject 1 was a currently rated Air Force navigator assigned to Ames and was the most experienced at taking sextant sightings. Subjects 2 and 3 had previous experience in sextant sighting during other sighting studies and were familiar with both sextants used in this study.

Subject 4 had no actual sighting experience prior to this investigation, but was intimately familiar with the data recording and data reduction procedures.

Training and Motivation

All four subjects were given training before they participated in the testing phase. Although subjects 1, 2, and 3 had considerable experience using a hand-held sextant, they had very little opportunity to use the D-9 sextant prior to the training phase of this study. Several practice sessions were held in the Ames Midcourse Navigation and Guidance Simulator, described in detail in reference 4, and two practice sessions were held at night in the 990 aircraft while it was parked on the ground. The first two flights were considered training and equipment checkout flights, while the last seven flights were the testing phase of the investigation.

An effort was made to insure a high degree of motivation in the subjects. All four subjects participated in each flight, providing an element of competition. Each subject was fully aware of the purpose and scope of the study and importance of his performance in the interpretation of the experiments. This study related directly to the work of all four subjects. Each subject was limited to a maximum of 10 sightings during each data run and alternated sighting stations every cycle to minimize fatigue.

Test Conditions

A total of nine flights were made between January and April of 1966. It was necessary to spread the flights over a four-month period because the moon's altitude (height above the horizon) had to be within the window field of view (35° to 70°) and the moon's azimuth had to be such that the aircraft could remain within the radar coverage while flying at a 90° angle to the moon's azimuth. These constraints left 3 to 5 days available each month for the flights. Then operational constraints such as aircraft maintenance problems, range availability, pilot availability, and weather conditions (high clouds, turbulence, take-off and landing conditions) had to be considered. It was possible to use the far lunar limb as a sighting target on only two of the nine flights and, therefore, only a limited quantity of this type of data was obtained.

The total time available for sighting on the moon was limited by the radar coverage, the speed of the aircraft, and the azimuth and altitude of the moon. The available inflight sighting periods, aircraft altitude and age of the moon for each flight are shown in the table below. An effort was made to fly as close to the full moon age as possible so that the brightness of the moon would be nearly constant, minimizing the possibility of any effect on the irradiance measurements.

Flight	Date	Available length of sighting period	*Moon age, days	Aircraft altitude, ft
1	1/13/66	No Moon	---	33,000
2	2/3/66	1h 35m	12.8	37,000
3	2/7/66	1h 25m	17.9	37,000
4	3/3/66	1h 20m	11.8	33,000
5	3/4/66	1h 25m	12.8	40,000
6	3/5/66	1h 25m	13.8	37,000
7	4/2/66	1h 25m	12.1	35,000
8	4/3/66	1h 25m	13.1	35,000
9	4/4/66	1h 40m	14.2	35,000

*Full moon at approximately 14 days.

RESULTS AND DISCUSSION

The sighting accuracy results, consisting of standard deviation and measurement bias error data, will be presented and discussed separately for each of the two sextants, hand-held and gimbaled. The data in the figures have been coded where necessary to identify the results of each run of 10 sightings made by each individual. A flagged symbol indicates that a subject made a second run of 10 sightings on a particular flight.

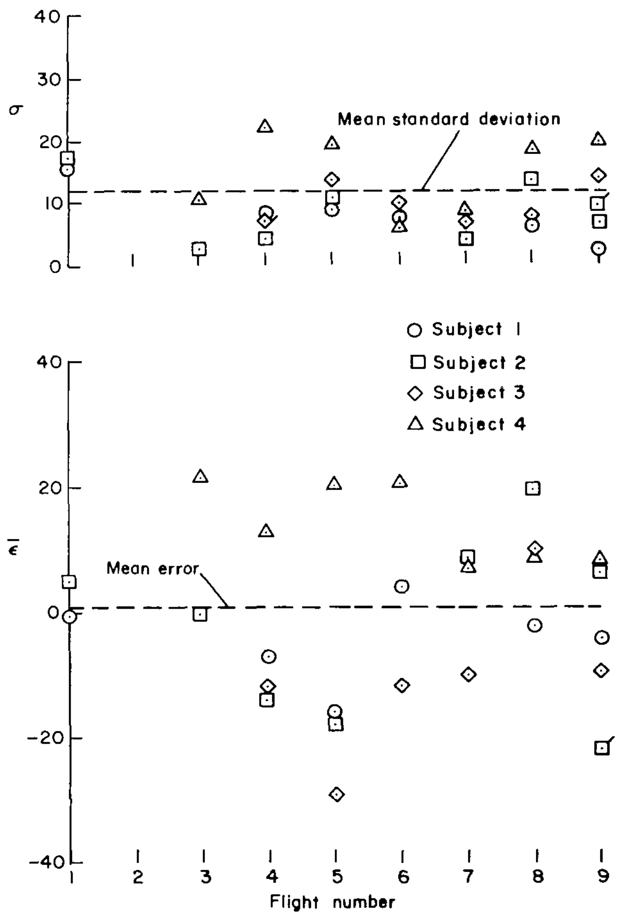


Figure 6.- Hand-held sextant, measurement errors, star/star targets.

Hand-Held Sextant Results

Shown in figure 6 are the results of hand-held sextant measurements of the angles between star-star targets. These data represent 27 data runs; each point is the result of 10 consecutive sightings; the four participants used six different target pairs. The target pairs used for the majority of the data were Betelgeuse and Bellatrix, and β Auriga and Capella. In figure 6 the standard deviation is for 10 consecutive measurement errors for each data run; the measurement error for that run is also shown. The dotted line indicates the mean value for all data. It should be noted that a positive measurement error indicates that the measured angle is larger than the actual angle, while a negative error indicates the opposite. The mean value of standard deviation for these data runs was ±12 arc sec and varied from ±3 to ±23 arc sec.

The range of values for standard deviation remains almost constant throughout the nine flights, indicating that the participants were well-trained with the sextant prior to the flights and that each had established his own level of proficiency. The mean measurement error for all subjects and all runs was +1/2 arc sec and the measurement error varied from -29 to +22 arc sec ($1\sigma = \pm 14$ arc sec) despite the fact that the measurements were made at high altitude where the atmospheric refraction corrections are small and also the probability of the occurrence of atmospheric anomalies is likely to be small. If the measurements of subject 1 are examined in detail, it may be seen that the mean measurement error was -4 arc sec while the measurement error varied from -16 to +4 arc sec ($1\sigma = \pm 7$ arc sec) for the six flights on which data were taken. For subject 2, the mean measurement error was -2 arc sec and the error varied from -17 to +20 arc sec ($1\sigma = \pm 14$ arc sec) for seven flights. Similar behavior is exhibited by the data of the other two subjects. Even though there are wide variations in the measurement error for each subject and between subjects, the standard deviations of measurement error appear to be quite consistent, as previously noted. A similar anomalous behavior of the measurement error has been noted previously in reference 5 and is attributed to the observers "personal equations." Since the data sample obtained during each aircraft flight was small due to the short time available for taking data, a definite assessment of the so-called "personal equation" for each observer was impossible, hence, the source of the anomalous variations in the measurement error for all data obtained for all targets by all subjects in these experiments is undetermined.

A typical target pair useful for space navigation is the moon (a near body) and a known star (a far body). Because of the moon's apparent size as seen from the earth, it is impossible to judge the center of the body accurately. Therefore, in this case and all similar cases where the near body is large, a limb or landmark on the near body is used for a sighting target. In this study, the lunar limb was selected as the near target.

The results of sighting on a star and the lunar near limb with the hand-held sextant are shown in figure 7 for 33 data runs of 10 sightings each. (The near limb is closest to the star target; the far limb is farthest from the star target.) All star targets used in combination with the lunar limb during this study were either first or second magnitude stars. Regulus, Pollux and Denebola were the star targets used for the majority of the star-limb type measurements.

The mean standard deviation for these runs (fig. 7) was ±15 arc sec. Again, the standard deviations, as seen in figure 7, are almost constant throughout the nine flights, supporting the conclusion that the subjects were well trained with the instruments prior to the flights. The range of standard deviations was from ±6 to ±24 arc sec. The mean error was -19 arc sec. A minus error would be expected on the near limb because of the irradiance effect. Irradiance effect is defined in this report as the apparent enlargement of the image of a bright surface against a darker background. The sketch below shows how irradiance is expected to influence the measurement of the angle between a star and the lunar limb.

As seen in this sketch, the irradiance effect would be expected to cause the observed angle from the star target to the near limb to be too small, producing a negative measurement error. Also, the observed angle to the far limb would be too large, producing a positive measurement error.

Figure 7 indicates a tendency for the measurement errors to decrease with observer experience. Whether this is due to the subjects knowing that a bias error due to irradiance existed and began to compensate unconsciously, or whether it is due to some other effect has not been determined.

Next, the far limb was used as the primary target. Less data was obtained on star-far limb targets because the moon age provided an opportunity to use the far limb for sighting only on two of the nine flights. The results from 7 data runs of 10 sightings each

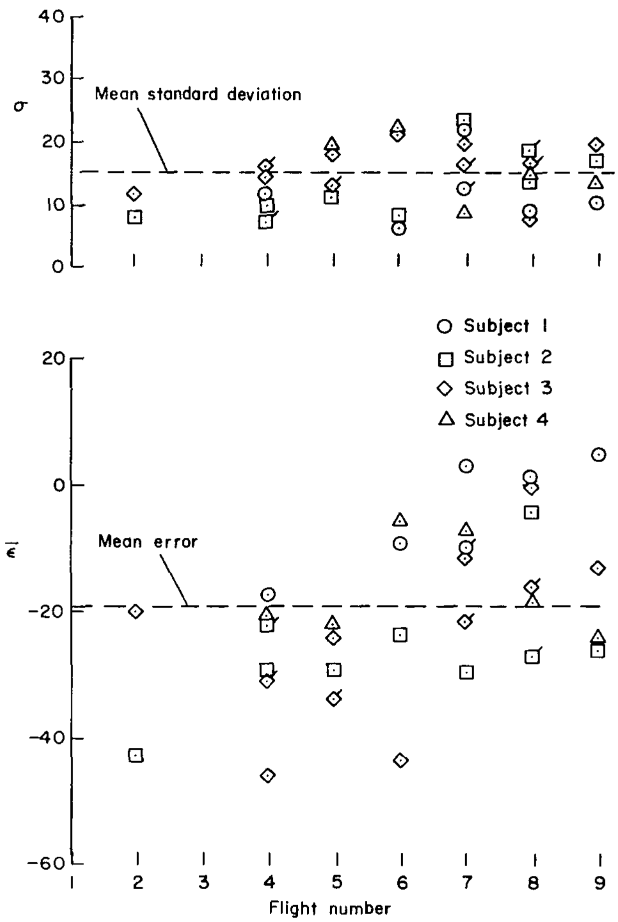
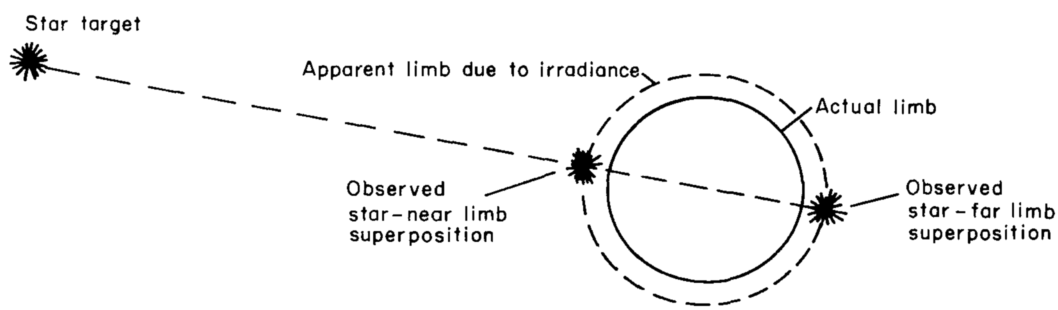


Figure 7.- Hand-held sextant, measurement errors, star/near lunar limb targets.



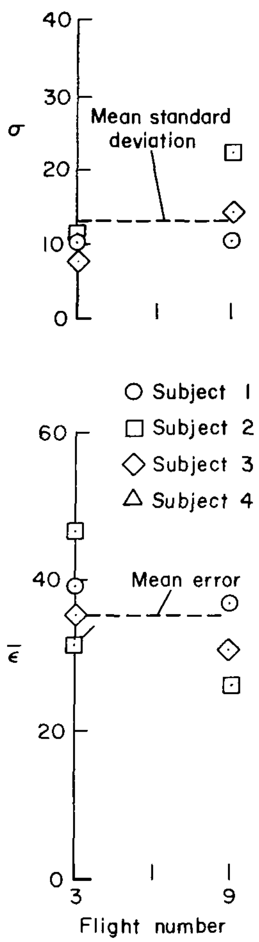


Figure 8.- Hand-held sextant, measurement errors, star/far lunar limb targets.

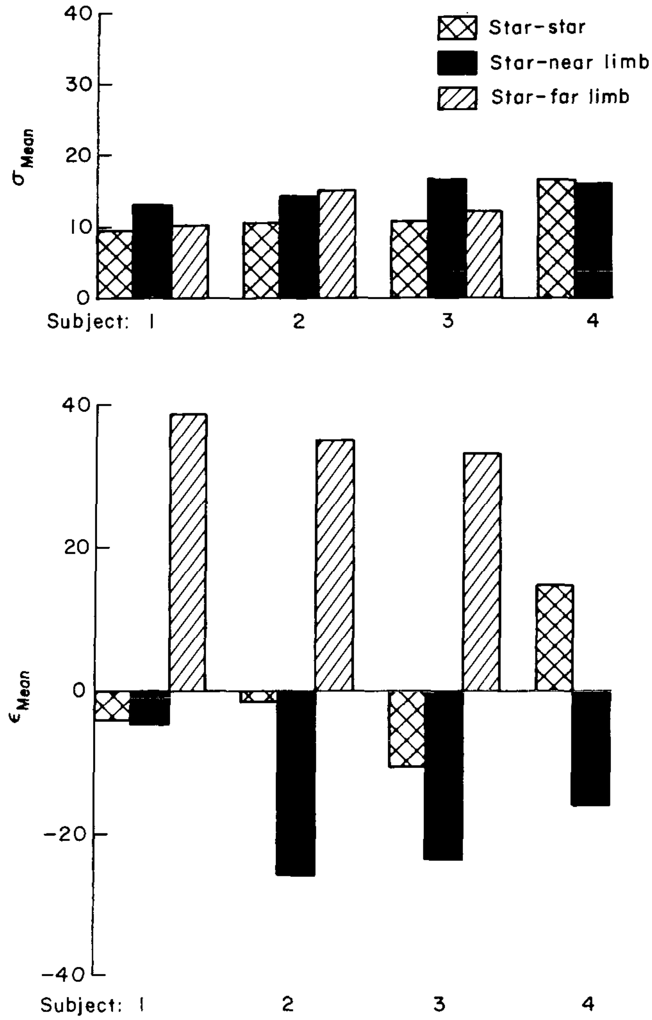


Figure 9.- The effect of target characteristics with hand-held sextant.

using the hand-held sextant are seen in figure 8. The mean standard deviation was ±13 arc sec and the mean measurement error was +35.5 sec, demonstrating that irradiance produced a positive error on the far limb. However, the effect of irradiance appears much larger on the far limb, since the magnitude of the average error is almost twice as large as on the near limb. No reason for this apparent inconsistency can be offered at this time.

A summary of standard deviation results for the hand-held sextant, plotted for each individual subject, is shown in figure 9. Values are plotted for the star-star, star-near-limb, and star-far-limb results. The degree of difficulty of measurement for the two types of target pairs is clearly shown by comparing the standard deviations for star-star targets with those for star-lunar limb targets. The star-limb standard deviations are consistently several seconds larger than the star-star results.

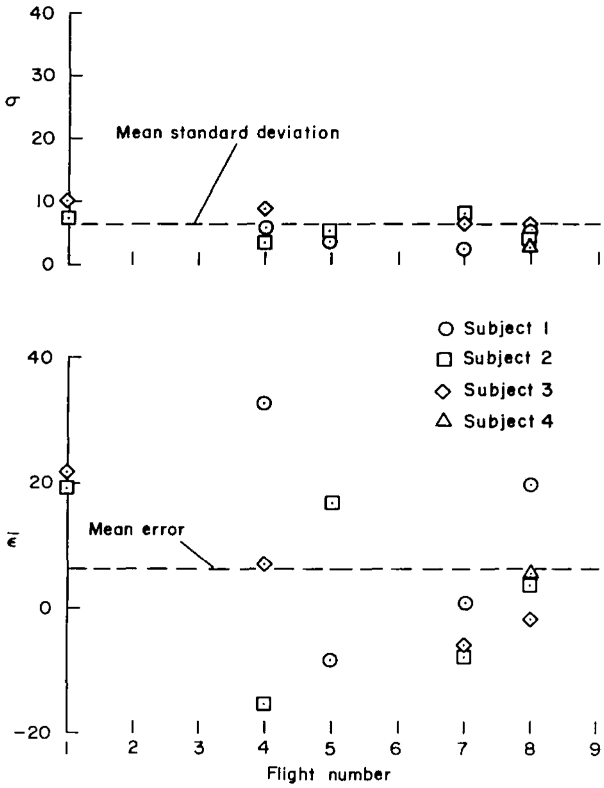


Figure 10.- Gimbal mounted sextant, measurement errors, star/star targets.

The measurement error results for all hand-held sextant sightings on the three types of target pairs are summarized for each subject in figure 9. The irradiance effect can be estimated in two ways. First, the average of the sum of the length of the near-limb and far-limb bars should represent the irradiance effect on a single limb. The average length is 25.5 arc sec; therefore the average irradiance is 25.5 arc sec per limb. A second choice of data for calculating the irradiance would be to use only the sightings obtained on the ninth flight (figs. 7 and 8) when the same star was used for both near- and far-limb measurements on the same flight. These data yield an average irradiance effect of 23 arc sec on each limb which compares well with that obtained by the previous method.

Gimbaled Sextant Results

The gimbaled sextant was more complex and less mobile than the hand-held sextant; as a result, the subjects made a total of 26 fewer data runs during the 9 flights.

The following data were obtained with the gimbaled sextant on the same three types of target pairs. The results for 14 data runs on star-star targets are plotted in figure 10. The mean standard deviation was ±6.5 arc sec and the mean error was +6.5 arc sec. The standard deviation data range from ±3 to ±10 arc sec, considerably smaller than the range of standard deviations for the hand-held sextant shown in figure 6. The measurement error results in figure 10 are widely scattered at the beginning, becoming more consistent on the later flights.

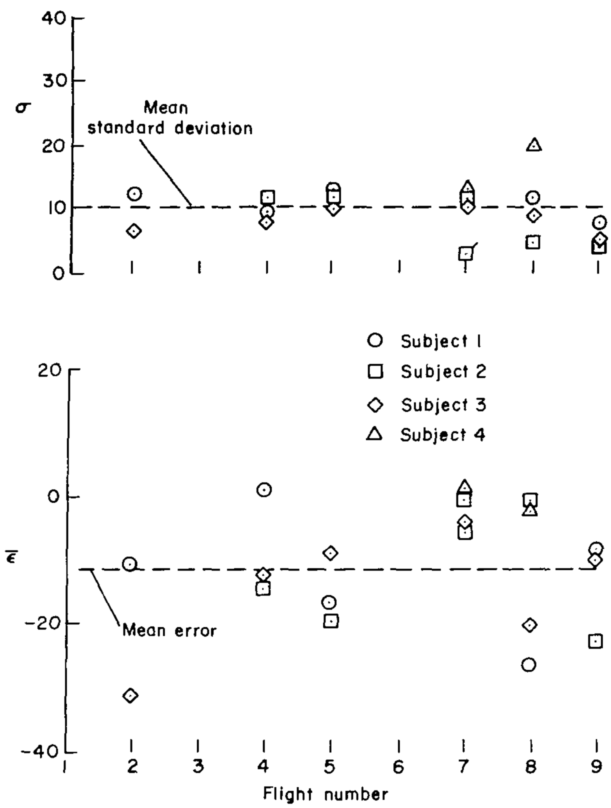


Figure 11.- Gimbal mounted sextant, measurement errors, star/near lunar limb targets.

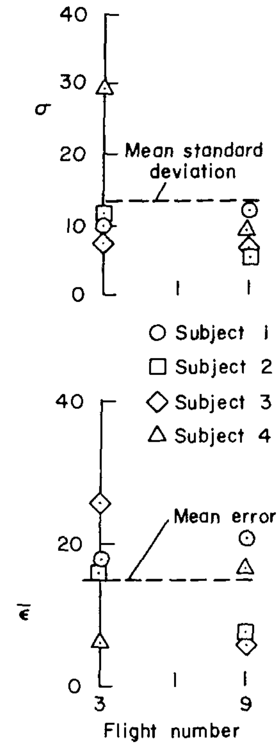


Figure 12.- Gimbal mounted sextant, measurement errors, star/far lunar limb targets.

The results from 19 data runs on star-near limb targets using the gimbaled sextant are shown in figure 11. The mean standard deviation for all runs was ±10.5 arc sec with a range of ±3 to ±20 arc sec. The mean measurement error was -11.5 arc sec. The error on the near limb would be negative if irradiance affected the measurements. By comparing the data of figure 11 with the corresponding data plotted for the hand-held sextant in figure 7, it appears that the advantages in magnification and readout accuracy provided by the gimbaled sextant more than offset its more complex operation. The gimbaled sextant data are much more consistent than those for the hand-held sextant and also have smaller mean errors and a smaller standard deviation of measurement errors for star-near limb targets. The results from 8 data runs on star-far limb targets with the gimbaled sextant are presented in figure 12. The mean standard deviation (fig. 12) was ±12.5 arc sec while the mean measurement error (fig. 12) was +15 arc sec.

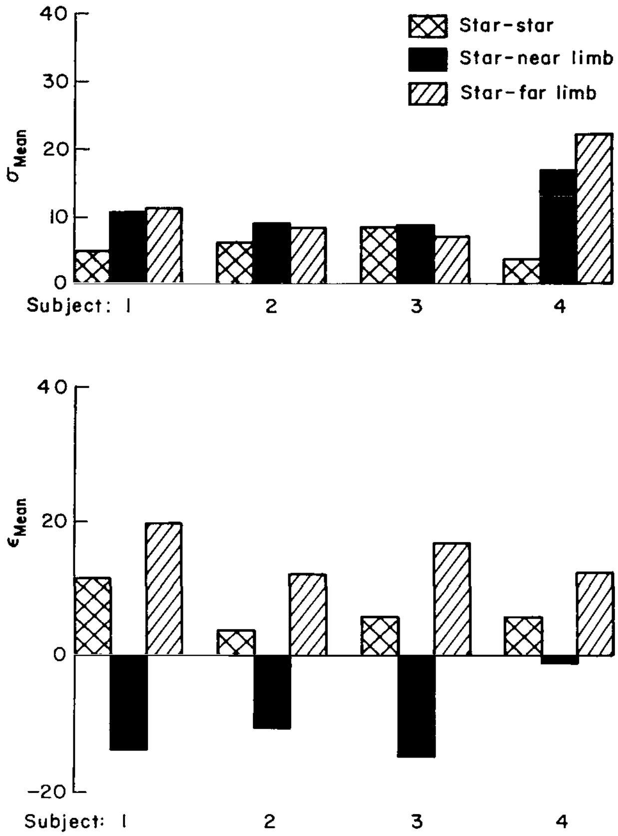


Figure 13.- The effect of target characteristics with gimbal mounted sextant.

A summary of the mean standard deviation for each subject using the gimbaled sextant is shown in figure 13 for star-star, star-near-limb, and star-far-limb results. This figure and the hand-held sextant results of figure 9 correlate quite well and the data in figure 13 support the previous conclusions concerning the relative degree of difficulty of the target pairs.

The mean measurement errors for all sightings with the gimbaled sextant on the three types of target pairs for each subject (fig. 13) are much more consistent than the same results for the hand-held sextant (fig. 9). Averaging the lengths of the near-limb and far-limb bars in figure 13 yields an average irradiance effect of 12.5 seconds for one limb. The data obtained on the ninth flight (figs. 11 and 12) when the subjects made near-limb and far-limb measurements on the same flight using the same star for the secondary target, show an average irradiance effect for one limb of 13.5 arc sec. The irradiance effect for the gimbaled sextant is about half the irradiance calculated from the hand-held sextant results. This difference is attributed primarily to the advantage of magnification for the gimbaled sextant (10 power compared with 4.5 power for the hand-held sextant).

The results of the aircraft studies correlate well with past simulator and ground observatory studies despite the presence of a pressurized window for the aircraft sightings. The standard deviations were slightly higher in the aircraft possibly because of the vehicle motion (vibration, turbulence, yaw, pitch, roll, etc.).

Subjects' Comments

The following comments on the utility of the two sextants are pertinent to understanding the good measurement performance obtained.

1. No difficulty was experienced in target identification through the 12 × 14 inch window.

2. The hand-held sextant was easy to operate and the angle readout was fast and simple. The weight of the sextant presented no fatigue problems

over the 10 consecutive sightings on each data run or over the 2 hour sighting period. The 4.5 power telescope on the hand-held sextant provided no difficulty in target identification, acquisition or superposition.

3. The gimbaled sextant was more difficult to use. The readout procedure was more complicated and lengthy. Target identification and acquisition was much more difficult with the 10 power telescope and the three gimbals than with the hand-held sextant. However, the subjects had more confidence in their decision on target superposition because of the greater magnification.

4. Normal aircraft motion in flight (yaw, pitch, and roll) provided no noticeable difficulty during the sighting periods. However, short periods of light turbulence experienced on several flights made sighting difficult, especially with the gimbaled sextant.

SUMMARY OF RESULTS

1. A mean standard deviation of measurement error of ±12 and ±6.5 arc sec was obtained when the angle between idealized star-star targets was measured with a 4.5× magnification hand-held sextant and a 10× magnification gimbaled sextant, respectively.

2. The mean standard deviation of measurement error was ±15 and ±10 arc sec for the hand-held and gimbaled sextants, respectively, when the angle between a star and the lunar limb (space navigation type targets) was measured.

3. The average lunar irradiance was about 24 arc sec when determined from hand-held sextant data and 13.5 arc sec when determined from gimbaled sextant data. The difference is attributed primarily to the advantage of magnification for the gimbaled sextant (10× versus 4.5× for the hand-held sextant) although some effect of filters may be present.

4. The standard deviation of measurement errors for the aircraft studies correlate well with past simulator and ground-observatory studies. The measurement errors for the aircraft studies vary widely as did the ground observatory data. The source of these variations may represent the "personal equation" of each observer.

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REFERENCES

1. Bader, Michel; Haughney, Louis C.; Stinnett, Glen W.; and Acken, Richard A.: Operational Report on the NASA 1965 Airborne Solar Eclipse Expedition. NASA TM X-1234, 1966.

2. Silva, Robert M.; Jorris, Terry R.; and Vallerie, Eugene M., III: The Air Force Space Navigation Experiment on Gemini. DOD/NASA Gemini Experiment D-9, Gemini IV and VII Flights. AFAL-TR-66-289, 1966.

3. Campbell, W. W.: The Elements of Practical Astronomy. Second ed., The Macmillan Company, London, 1929.

4. Lampkin, Bedford A.; and Randle, Robert J.: Investigation of a Manual Sextant-Sighting Task in the Ames Midcourse Navigation and Guidance Simulator. NASA TN D-2844, 1965.

5. Smiley, C. H.; and Quirk, M.: Personal Equation and the Modern Marine Sextant. Navigation. J. Inst. Navigation, vol. 3, no. 1-10, Dec. 1953, pp. 353-356.

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